New QCD phenomena in forward pA domain: forward hadron spectra, leading twist shadowing, parton correlations, etc

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Outline

- Interpretations of the BRAHMS data - what is next.
- Small x nuclear parton densities
- Probing onset of the black body limit/saturation regime in the leading hadron spectra for central pA collisions
- Four--jet production: Study of multiparton correlations in nucleons and nuclei
- Color fluctuations in nucleons:

Exclusive hard diffraction: mapping of the qqq proton wave function.

Will not cover:

Color fluctuations in soft processes: inelastic diffraction.
Incoherent phenomena: Proton-ion collisions with a hard trigger probe transverse nucleon structure

Two indications of interesting new forward physics in dA scattering - suppression of the J/ψ forward production and the BRAHMS forward π^- data.

J/ψ data - the simplest assumption is that the main production mechanism is interaction with the hard small x gluon field of nucleus at $x_A = \frac{m^2_{J/\psi}}{x_F s_{NN}}$

The data are consistent with the leading twist shadowing of gluons of the magnitude discussed by FGS. Open question - other phenomena.

More is known about forward pion production - at least at the level of the possibility of asking questions. The following few slides are are a result of the discussions with Werner Vogelsang.

Open questions in the forward pion production in NN scattering relevant to interpretation of the BRAHMS data.

- For what x, pt pQCD works for forward production?

ISR data for PT < 1.4 GeV/c for large x_F >0.3-0.4 find

$$x_F \frac{d\sigma^{pp\to\pi^+X}}{dx_F} \quad xu(x), \qquad x_F \frac{d\sigma^{pp\to\pi^-X}}{dx_F} \quad xd(x).$$

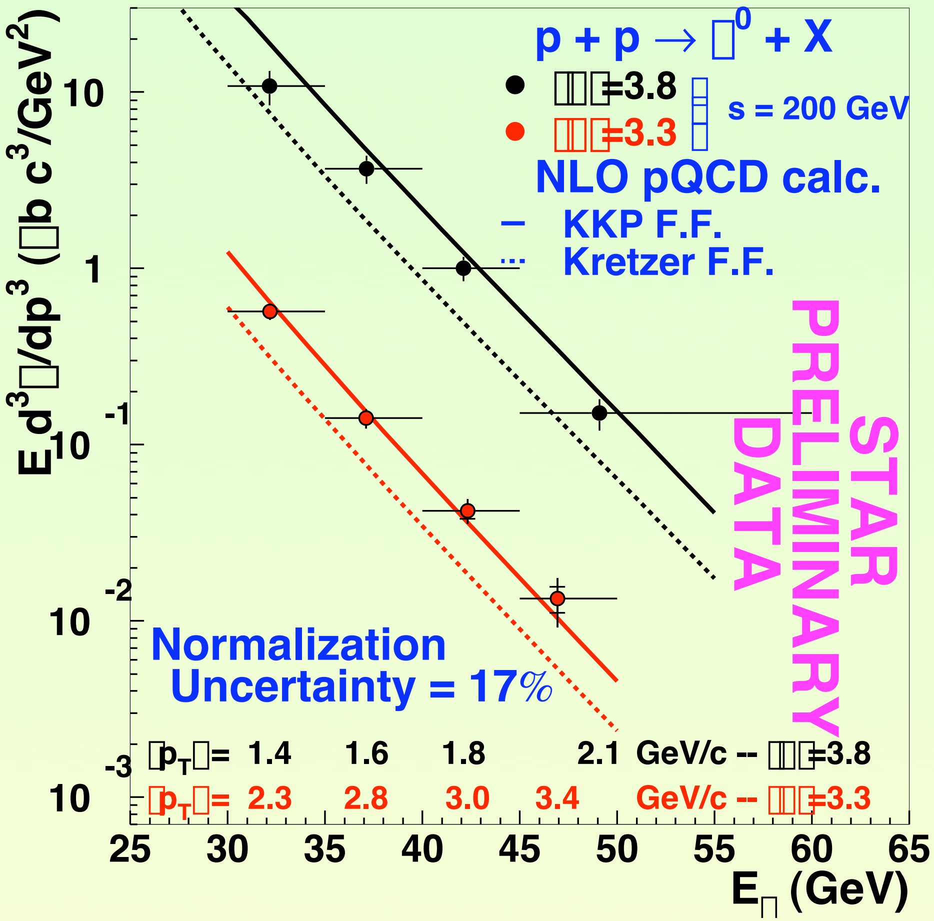
This is much harder spectrum than pQCD expectation. A natural interpretation the forward quark merges with spectator antiquarks and possibly gluons.

The lowest order pQCD diagram which dominates for $x_F \to 1$

and intermediate pt is the fragmentation of $q\bar{q}g$ into pion leading to

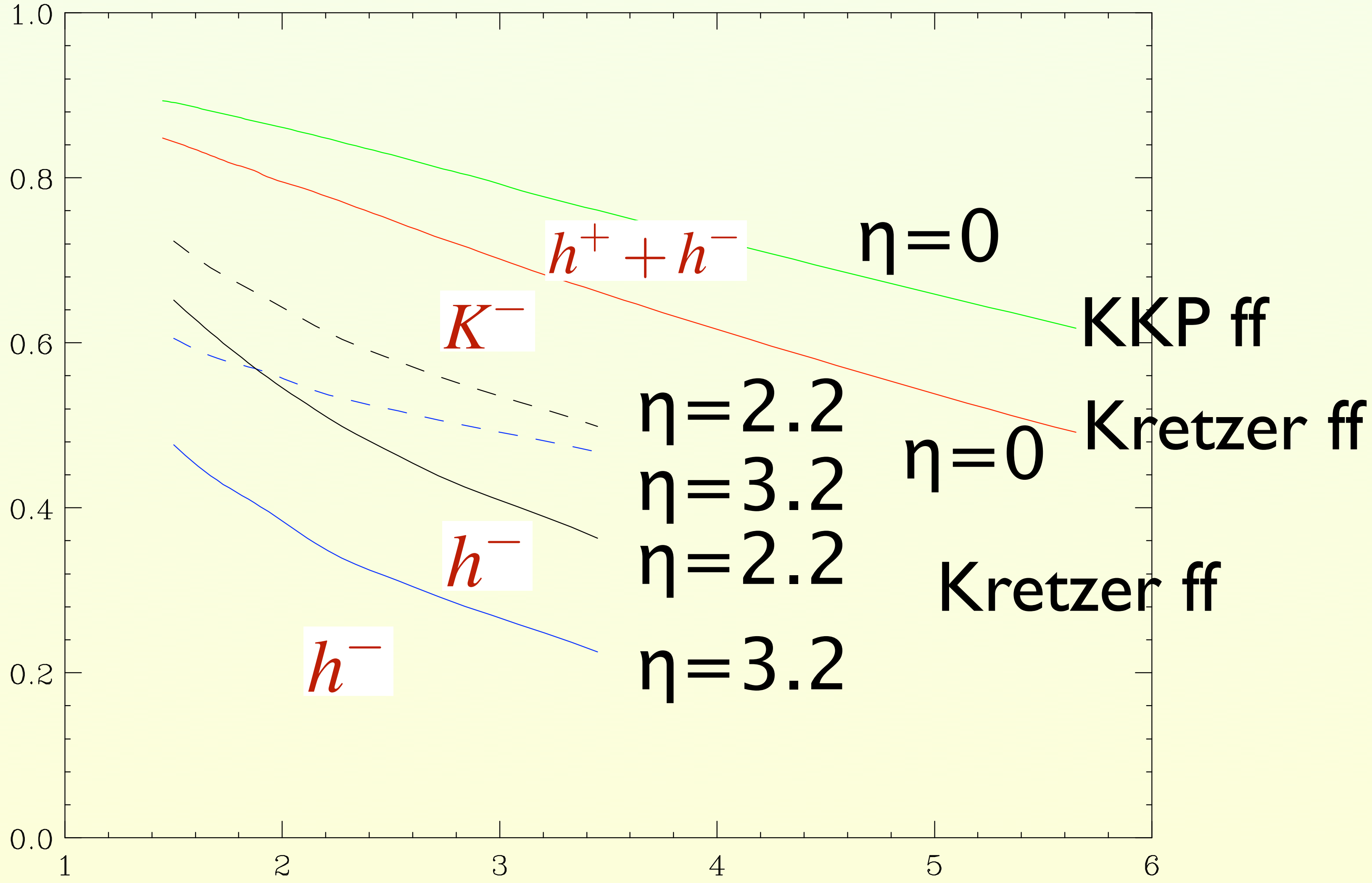
$$x_F \frac{\sigma^{NN\to\pi+X}}{dx_F} \quad (1-x_F)^2$$ which is consistent with x>0.8 data (FS80)

The STAR data appear to be consistent with pQCD calculations of Vogelsang et al. However they are sensitive to the gluon fragmentation which contributes !!! even at the highest pion energies (next transparency)



Guess : ≥ 50% of the cross section is pQCD

Relative contribution of gluons to the total yield in $pp \to h + X$.



- How large is correction for isospin effects?

Correct quantity to compare to the current pQCD calculations is :

$$\frac{2x_F \frac{d\sigma^{dA\to\pi^-+X}}{dx_F}}{x_F \frac{d\sigma^{nN\to\pi^-+X}}{dx_F} + x_F \frac{d\sigma^{pN\to\pi^-+X}}{dx_F}}$$

→ How small is $\frac{x_F \frac{d\sigma^{pp\to\pi^-+X}}{dx_F}}{x_F \frac{d\sigma^{nN\to\pi^-+X}}{dx_F}}$?

Data from ISR: π^-/π^+ for x>0.3 is < 0.5, weakly depends on $p_T\ for\ p_t \le 1.4\ GeV/c$ and reaches 0.2 for the highest x.

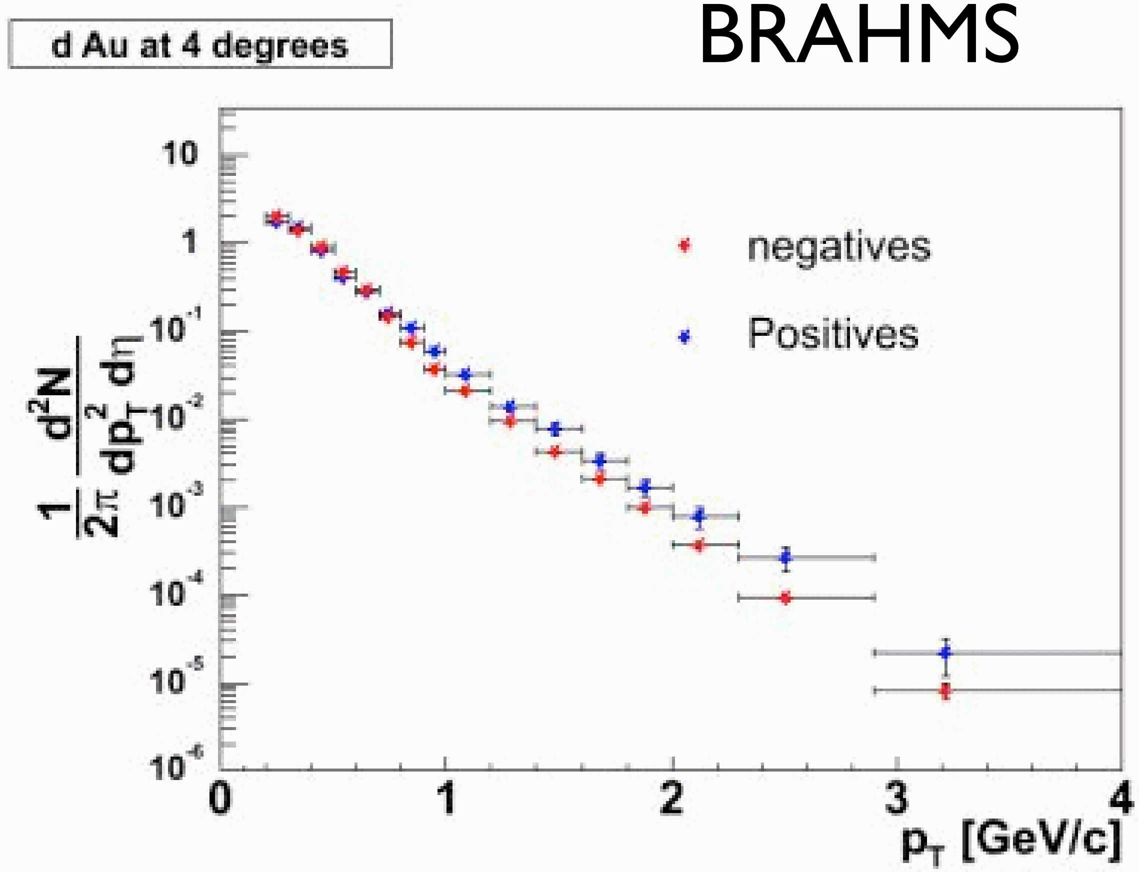
pQCD for BRAHMS kinematics for η=3.2 is 0.6 for p_t=2.15 and drops to 0.43 for p_t=3.45 since quarks dominate and u/d > 3.

⟹ Correction to convert from $pp\to\pi^-\ to\ pN\to\pi^- + nN\to\pi^-$

is ***at least a factor of 1.5.***

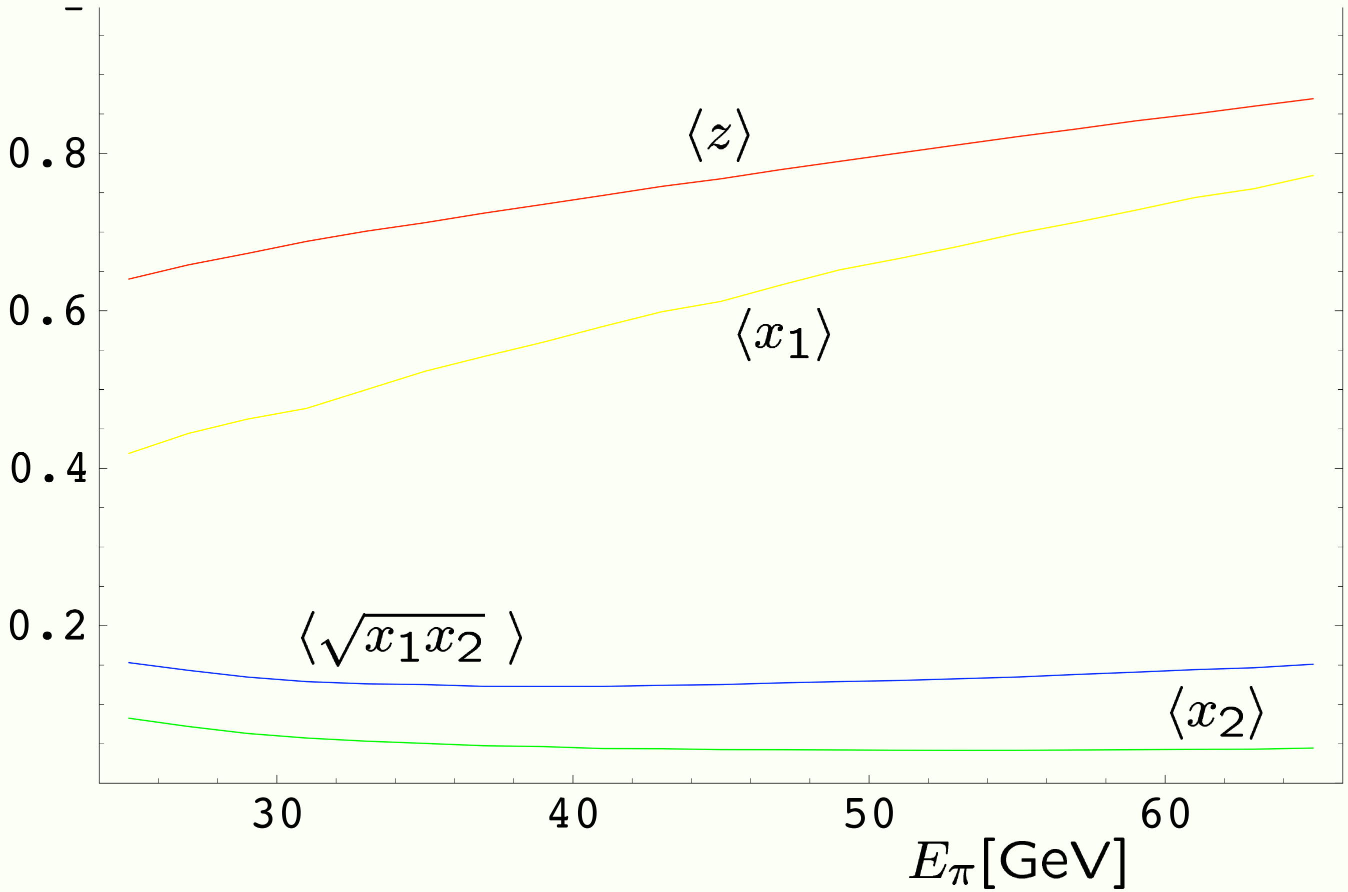
There appears to be some evidence for non LT effects at highest PT:

BRAHMS



Requires $p/\pi^+ \sim 1$ impossible in LT pQCD

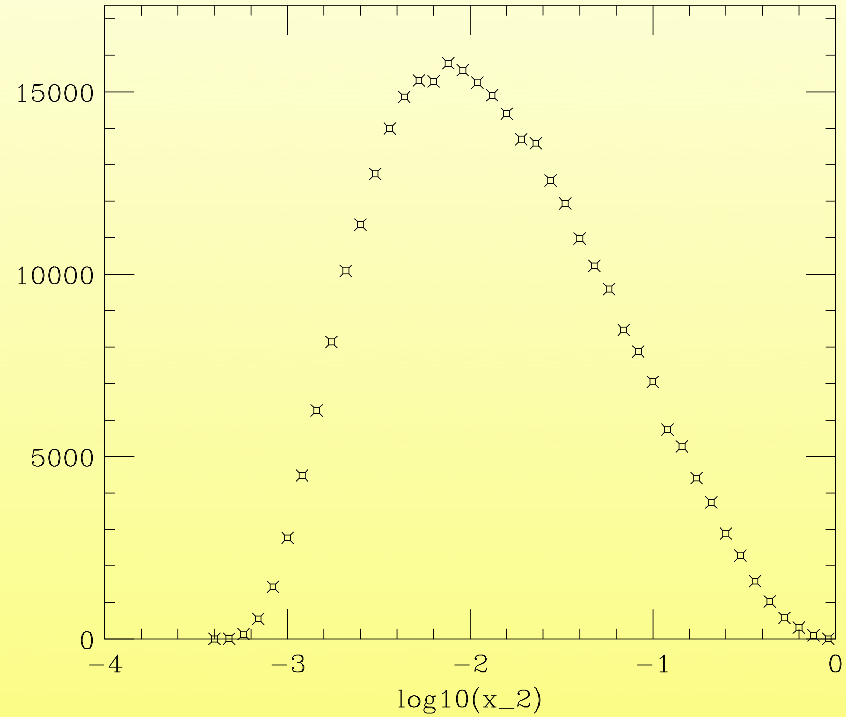
η=3.8



0.8
0.6
0.4
0.2
30
40
50
60
E_π[GeV]
$\langle z \rangle$
$\langle x_1 \rangle$
$\langle \sqrt{x_1 x_2} \rangle$
$\langle x_2 \rangle$

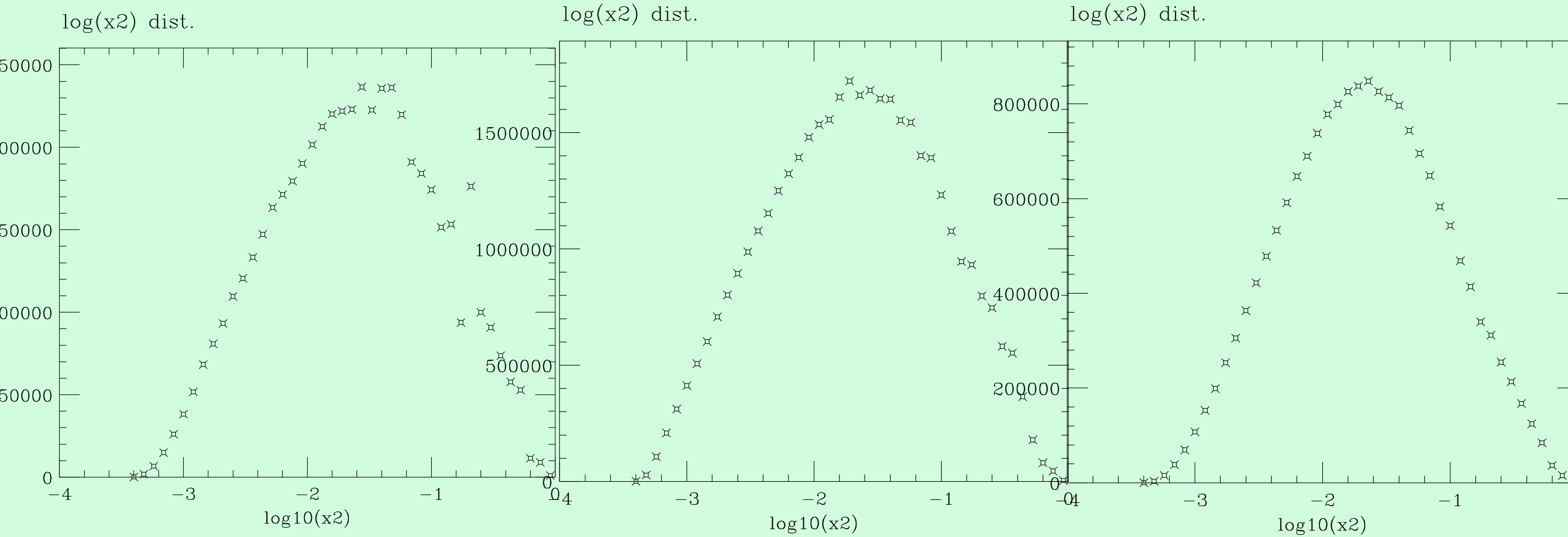
What values of x_2 are important?

$\sqrt{s} = 200GeV, \langle \square \rangle = 3.8, p_t = 2GeV/c$



Area under the curve illustrates relative contribution of different regions of x_2
Median of the integral is $x_2 \sim 0.013$, however mean value of x_2 is much larger.

$< \square >= 3.2,\ P_T = 1.5\ GeV/c$



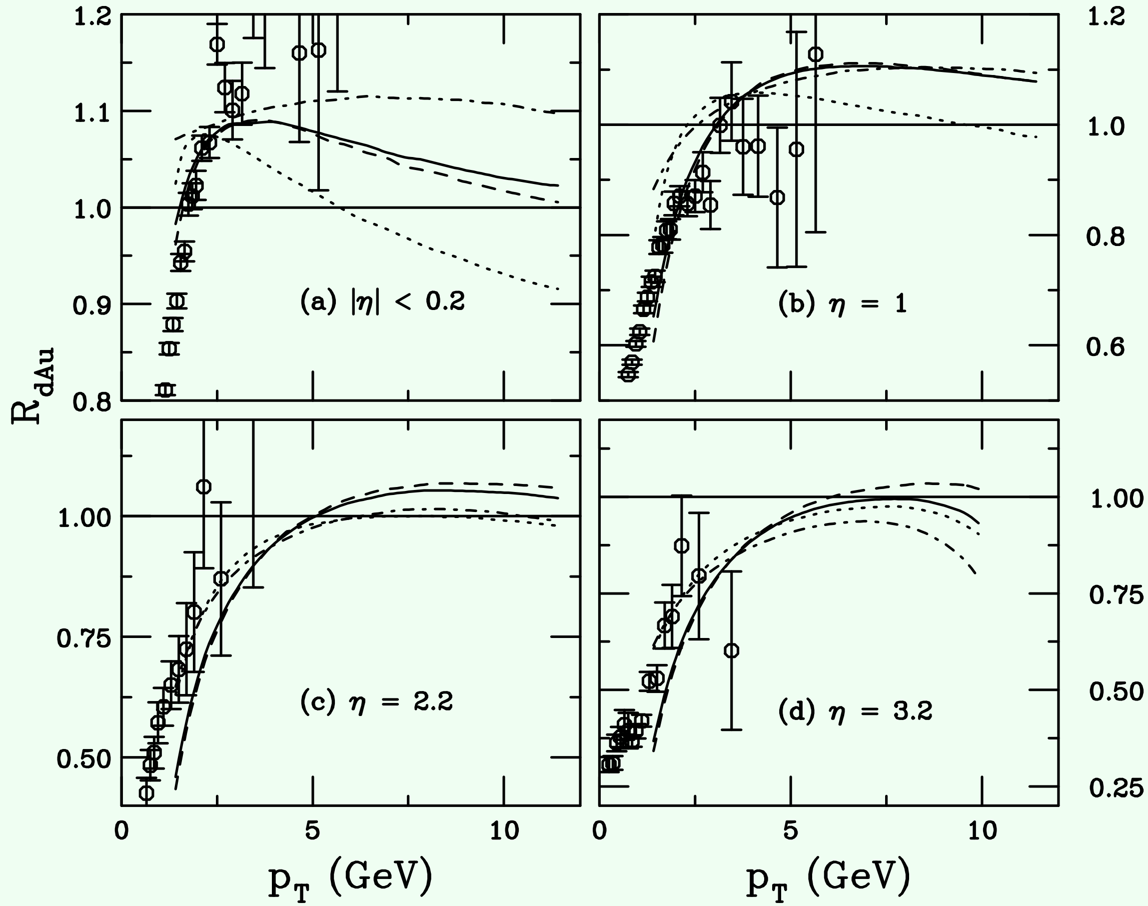
Kretzer f.f. h-

KKP pi0 NLO

KKP pi0 LO

Shape is nearly the same for different pion channels. It is a also practically the same in LO and NLO. Median x is between 0.02 and 0.024.

Hence a significant part of the cross section originates from the x-range where gluons are shadowed in nuclei.



R.Vogt - May 2004

LO calculation

Check how big are NLO effects? Sensitivity to the input nucleon pdfs?

R_{dA} for charged pions (dashed) and kaons (dot-dashed) as well as protons and antiprotons (dotted) and the sum over all charged hadrons (solid) for deuteron-gold collisions $\sqrt{S_{NN}} = 200\ GeV$ as a function of p_T. The results for homogeneous shadowing with the FGS parameterization are compared to the BRAHMS data in the following eta bins: (a) $\eta \leq 0.2$;(b) $\eta = 1$; (c) $\eta = 2.2$ and (d) $\eta = 3.2$.

⇒ LT nuclear gluon shadowing maybe relevant, but further tests/calculations are necessary in more simple processes like Drell-Yan process, photon-jet production. In any case the current comparison does not include the correction for $pp \to \square^{-}\ to\ pN \to \square^{-} + nN \to \square^{-}$

Several other effects may contribute/dominate:

- Suppression of the non LT effect of merge with spectator partons

MS & Berrera 96, MS &Gerland & Dumitru 03

- Close to the Black body limit energy - in difference from the eikonal model expectations the parton energy losses should be fractional FS03. Relevant for large x gluons but not quarks at RHIC. Suppression of the component of the leading pion spectrum due to the gluon fragmentation.

Suppression of gluons ⇒ change in the composition of hadron spectrum with A. The simplest

tests: *increase of* π^{+}/π^{-} *ratio with A in pA collisions,*

difference between π^{-} suppression *pA and dA,...*

Main trusts for the future forward pA physics at RHIC

- Measurement of nuclear parton densities in wide range of Q^2, x -- down to $x \sim few\ 10^{-4}$, search for shadowing and nonlinear effects at large Q^2

- pA provides clean ways to measure novel QCD phenomena related to the onset of black body limit, correlations of hard partons, correlations between soft and hard partons and multiparton correlations in nucleons and nuclei

Forward Hard physics at RHIC compared to SPS

- A parton in nucleon with resolution x_N and given p_t is sensitive to gluons at

$x_A \sim 4p_t^2/s_{NN}x_N$: $x_N = 0.3, p_t = 2\ GeV/c \Longrightarrow x_A^{RHIC} = 5 \cdot 10^{-4}, x_A^{SPS} = 5 \cdot 10^{-2}$

$\Longrightarrow$ Gain in nuclear gluon density by a factor of two-four. Also "densities/unit area" are much larger than in the nucleon case.

- Partons passing through the nuclei are experiencing significantly larger distortions - both p_t broadening and energy losses; for $p_t \leq 1$ GeV/c the interaction of leading partons in the proton projectile appears to be close to the black body limit.

- Interactions with the partons in the nucleus with $x \leq 0.01$ involves several nucleons of the nucleus - leading twist nuclear shadowing.

$\Longrightarrow$ It is necessary to check at what minimal virtualities factorization will be valid for hard processes.

General conclusions from the previous studies

ACSW, FELIX

Hard Cross sections are large for high precision measurements enough even for the processes with the smallest cross section – Drell – Yan, jet - photon that x, Q range is mostly determined by the acceptance of a detector and the range of virtualities where hard physics dominates.

$x_1 \equiv x_p \; up \; to \; x_p \sim 0.5 \; can \; be \; used$

$\Longrightarrow$ For 250 GeV nucleon x 100 GeV/nucleus collisions

For Drell-Yan with mass of 4 GeV

$x_A \; down \; to \; 3 \cdot 10^{-4}$!!!

Can we expect large nuclear modifications based directly on the nuclear DIS data?

NO !!!

At small x where shadowing for γ^*A scattering is significant higher twist effect appear to be important.

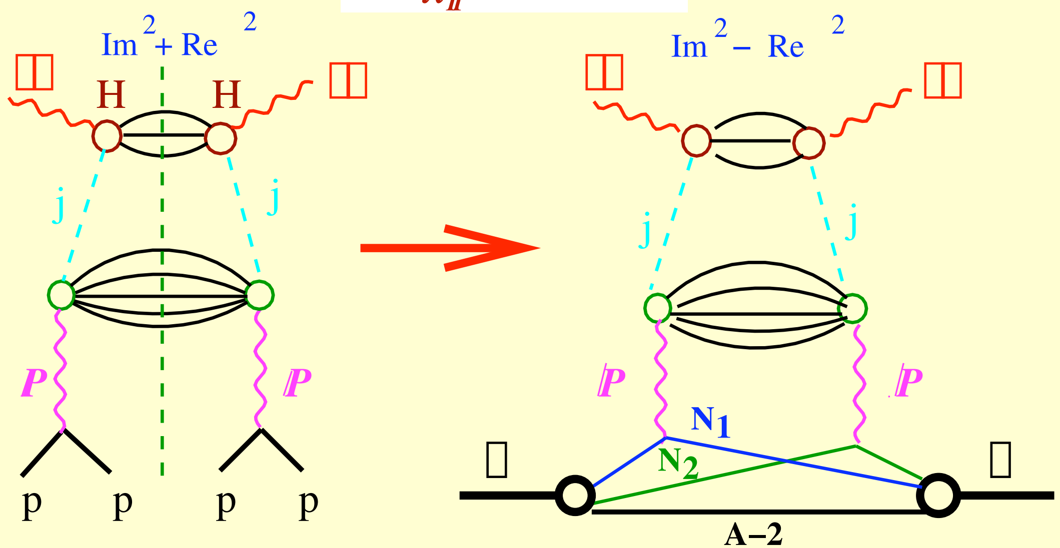
Frankfurt, Guzey, MS: ~ 50% ; Qiu, Vitev - 100%

in particular very large contribution of $\rho-$meson production which is definitely a higher twist

Solution for obtaining LT nPDFs:

Combine the Gribov theorem which relates diffraction in the scattering off a nucleon and nuclear shadowing ***and provides essentially model independent description of the current DIS data (effectively including higher twist effects)***, and the Collins factorization theorem for hard diffraction in DIS to express unambiguously the leading twist nuclear shadowing through the diffractive parton densities: $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$

FS98



Hard diffraction

off parton "j"

Leading twist contribution

to the nuclear shadowing for

structure function f_j (x,Q^2)

Theorem: in the low thickness limit (or for x>0.005)

$$f_{j/A}(x,Q^2)/A = f_{j/N}(x,Q^2) - \frac{1}{2+2\eta^2}\int d^2b \int_{-\infty} dz_1 \int_{z_1} dz_2 \int_x^{x_0} dx_{I\!P} \cdot$$

$$\cdot f^D_{j/N}\left(\beta, Q^2, x_{I\!P}, t\right)\Big|_{k_t^2=0} \; \rho_A(b,z_1)\, \rho_A(b,z_2)\; \mathrm{Re}\left[(1-i\eta)^2 \exp(i x_{I\!P} m_N (z_1 - z_2))\right],$$

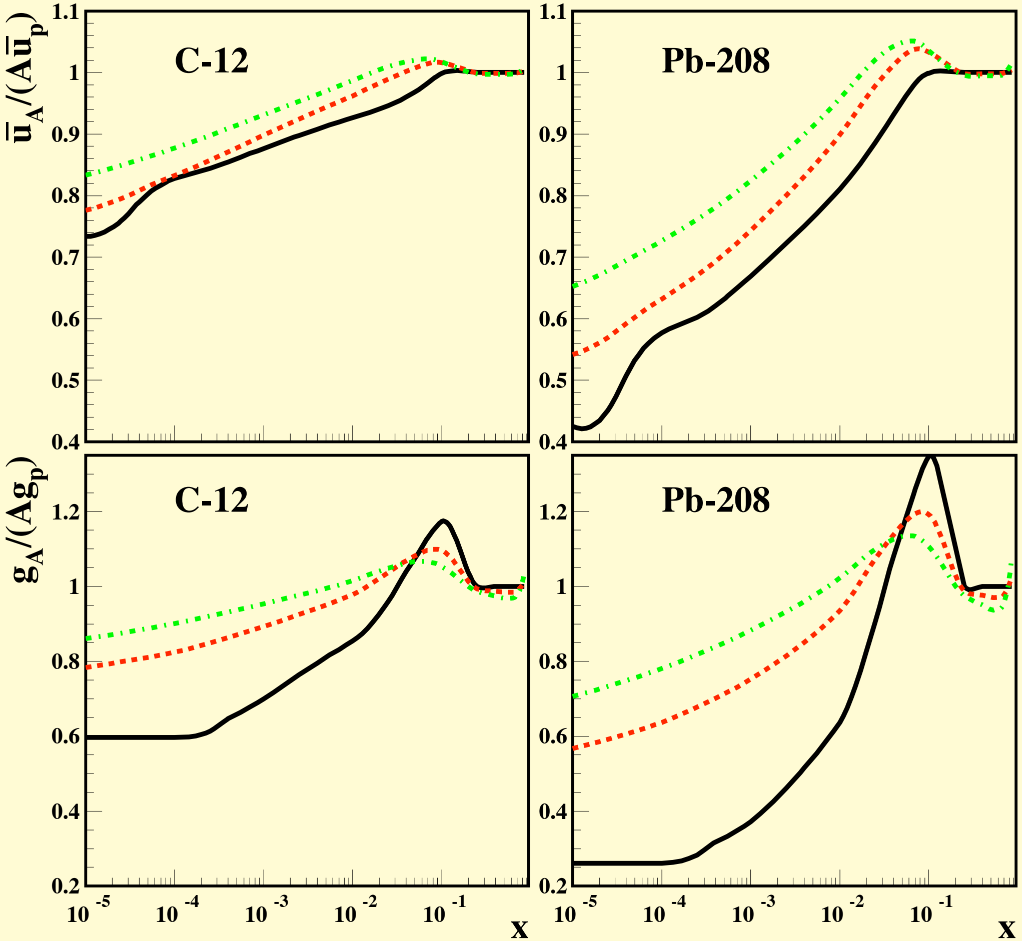
where $f_{j/A}(x,Q^2), f_{j/N}(x,Q^2)$ are nucleus(nucleon) pdf's,

$\eta = ReA^{diff}/ImA^{diff} \approx 0.3,\ \rho_A(r)$ nuclear matter density.

$x_0(quarks) \sim 0.1,\ x_0(gluons) \sim 0.03$

Next step: use the HERA measurements of diffractive quark and gluon PDFs which indicate dominance of the gluon induced diffraction to calculate gluon and quark shadowing.

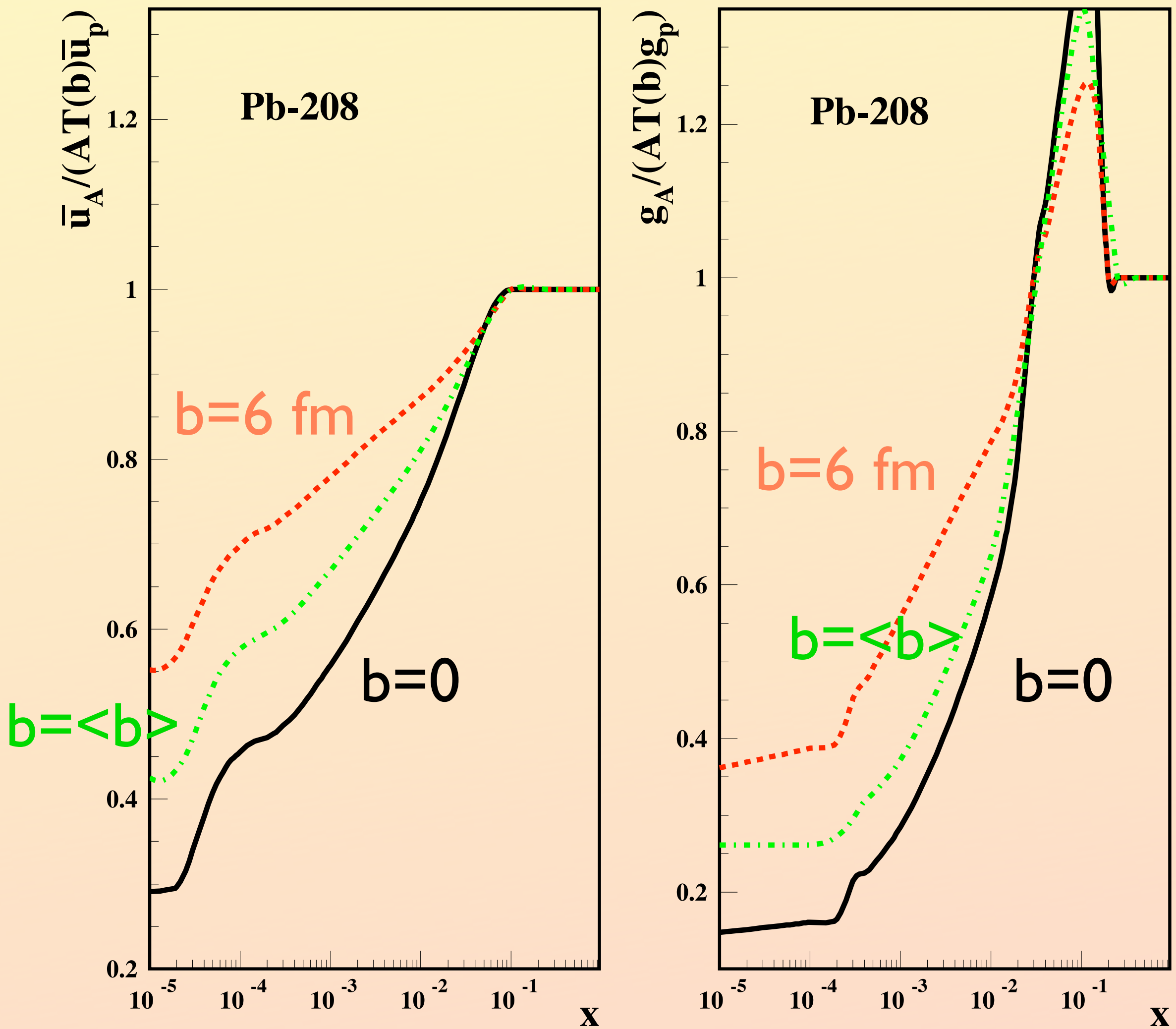
Detailed analysis in Guzey, FS & McDermott. Numerical studies include higher order rescattering terms and HERA measurements of diffractive quark and gluon PDFs which indicate dominance of the gluon-induced diffraction to calculate gluon and quark shadowing.



Dependence of G_A/AG_N and $\bar{q}_A/A\bar{q}_N$ on x for Q=2 (solid), 10 (dashed), 100 GeV (dot-dashed) curves calculated using diffractive parton densities extracted from the HERA data, the quasieikonal model for $N \geq 3$, and assuming validity of the DGLAP evolution.

Large gluon shadowing at x~ 0.003 agrees well with dA RHIC data: PHENIX data on J/ψ production and may contribute to the leading pion (y~3) suppression reported by BRAHMS.

Shadowing strongly depends on the impact parameter. Dependence of parton densities on impact parameter in the quasieikonal model (GFS -03) at Q=2 GeV.



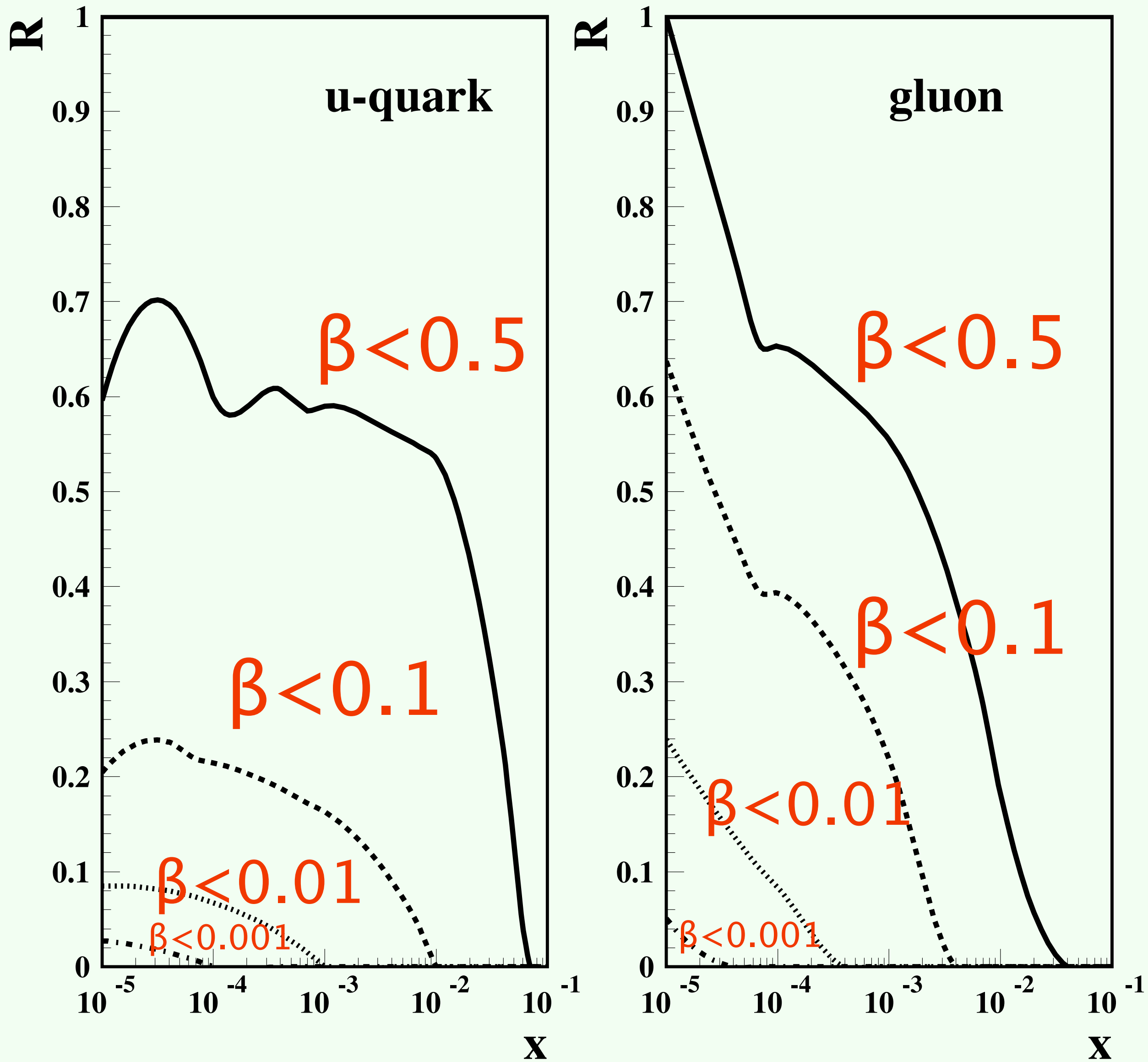
b-dependence can be studied experimentally by comparing the rapidity dependence of the hard processes in peripheral and central collisions

Conclusion: Large LT shadowing effects both for quarks and gluons in the forward RHIC kinematics.

Comment: Connection to the leading twist shadowing in Color Glass Condensate model.

In current version of CGC LT shadowing is also present. However the main contribution corresponds to diffraction into large masses, such that $\beta = x/x_P = Q^2/(Q^2+M^2) \ll \langle\beta\rangle \sim 0.5$.

This is indeed the case in LT approach for $x \ll 10^{-3}$. However dominance of this regime occurs for very small x only. We find that even in the forward RHIC kinematics average β are of the order 0.3-0.5 - see next slide.



Contribution to the LT shadowing due to integral over β smaller than a given maximal value.

The growth of parton densities at small x cannot continue without taming. The simplest argument is based on unitarity for the scattering of small dipoles of transverse size d. (FS & Koepf 96)

In the case of nuclear targets the analysis involves modeling the LT gluon shadowing. A convenient quantity to separate the scattering at the central and large impact parameters is the profile functions, $\Gamma(b)$

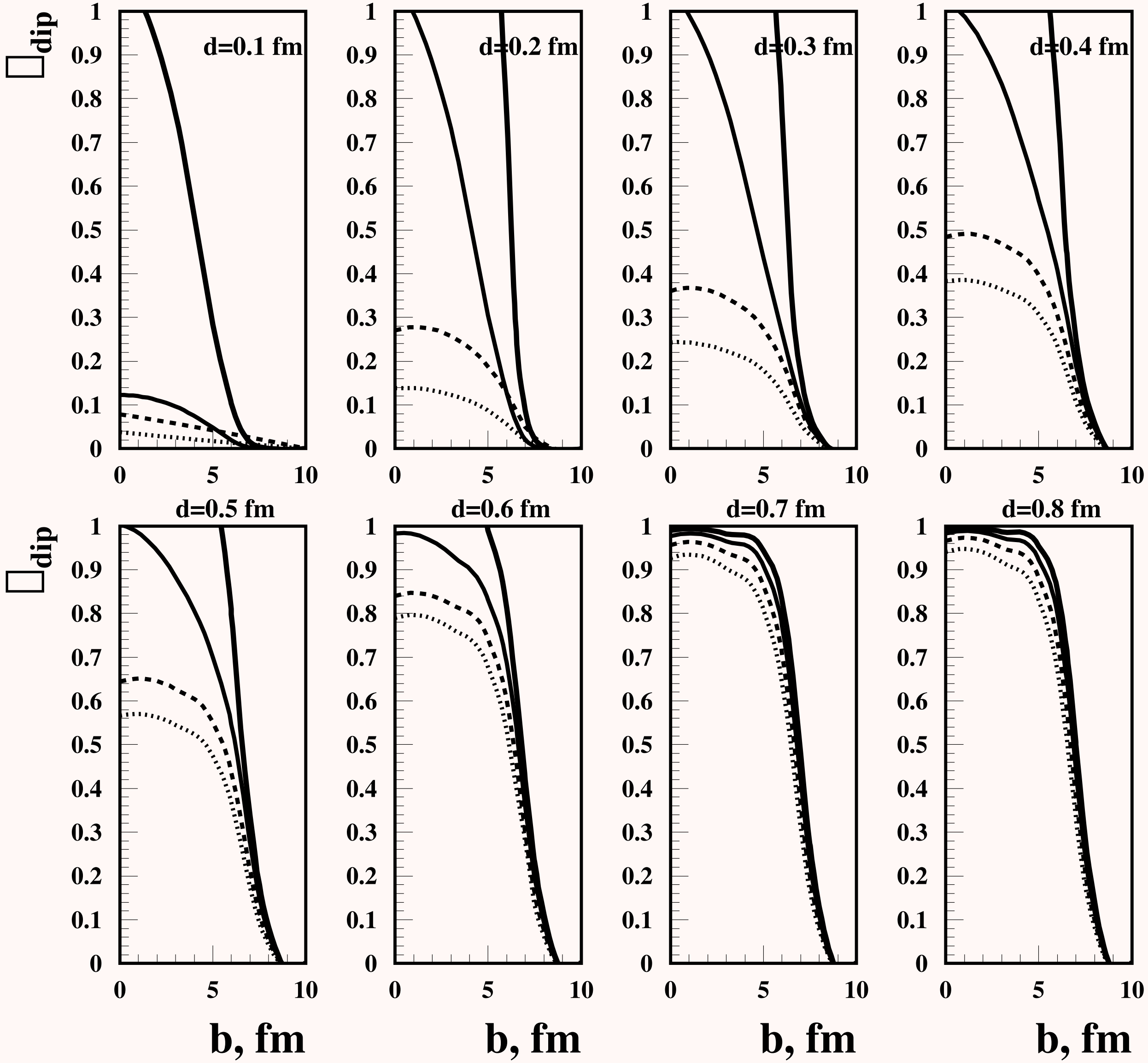
$$\Gamma_h(s,b) = \frac{1}{2is}\frac{1}{(2\pi)^2}\int d^2\vec{q} e^{i\vec{q}\vec{b}} A_{hN}(s,t) \quad ;$$

$\Gamma(b) = 1 \equiv \sigma_{inel} = \sigma_{el}$ Black body limit (BBL)

We find: $q\bar{q}$ interaction remains strong for $x \sim 10^{-3}$ up to

$$p_t \sim \frac{\pi}{2d} \sim 0.8 GeV$$

For gg color singlet dipoles interaction is stronger by a factor of 9/4 so in this case BBL range is larger.



Curves are for

$$x = 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}$$

$$d = 0.3\ fm \approx p_T \sim\ 1\ GeV/c$$

Probability of inel. interaction:

$$P(b) = 2\ Re\Gamma(b) - |\Gamma(b)|^2$$

$$P(b) = 0.64\ for\ \Gamma(b) = 0.4$$

$$corresponds\ to\ d = 0.3\ fm\ at\ x = 10^{-3}$$

The hadronic configuration- lead profile function. (Rogers et al, 03)

Situation is likely to be somewhat closer to BBL than according to this estimate due to inelastic diffraction contribution.

Signals of proximity to BBL

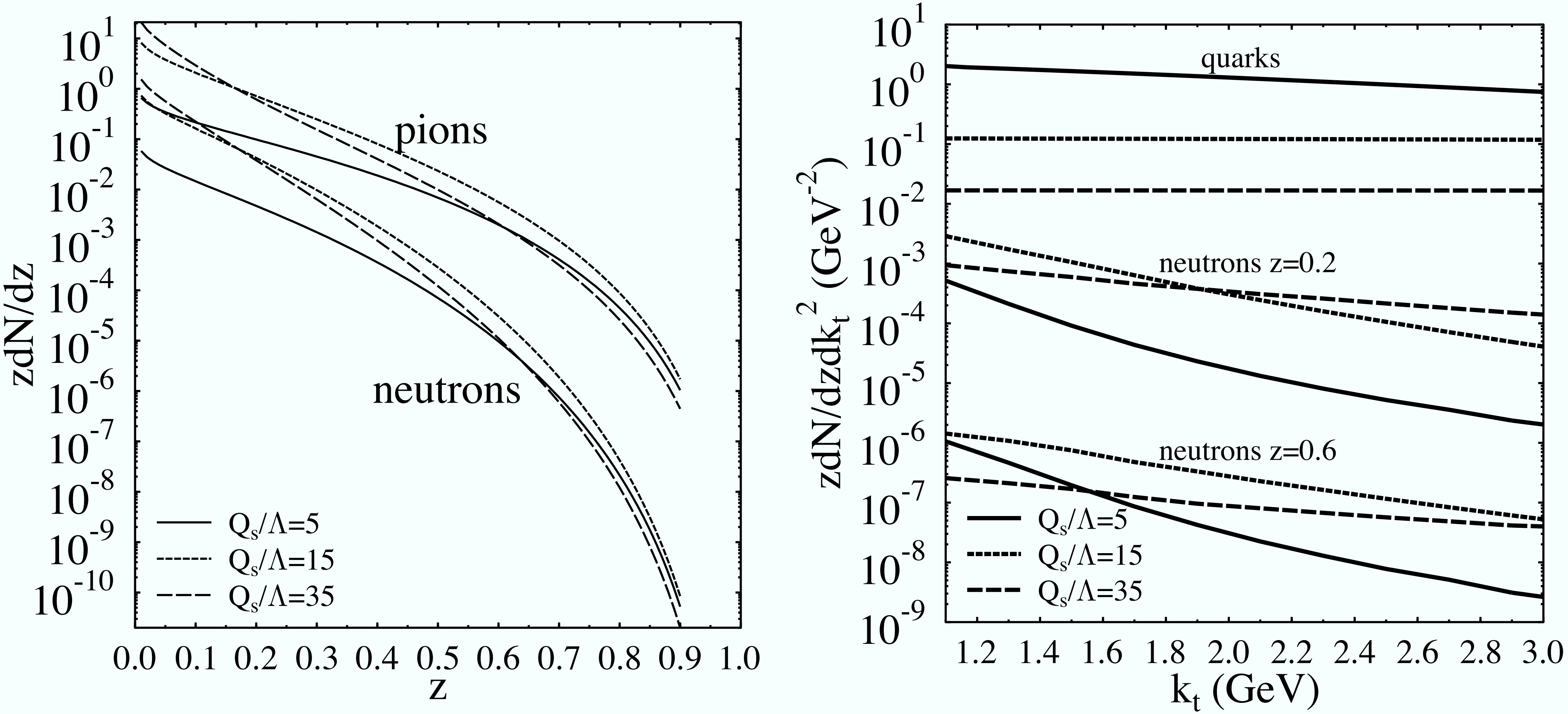
- Broad p_t distribution for ${}^{+}\ {}^{-}$ production, dijets (recent calculations in the Color Glass condensate model Gelis & Jalilian-Marian & Dumitru)

- ``Anomalous" dependence of the dimuon cross section on $M^2_{\mu^+\mu^-}$

$$\frac{d\sigma(p+A\to\mu^+\mu^-+X)}{dx_A dx_p} = \frac{4\pi\alpha^2}{9}\frac{K(x_A,x_p,M^2)}{M^2}F_{2p}(x_p,Q^2)\cdot\frac{1}{6\pi^2}M^2\cdot 2\pi R_A^2\ln(x_0/x_A)$$

the K-factor is approximately the same as in LT.

- Strong suppression of the leading hadron production combined with a very significant broadening of the p_t spectrum, Dumitru, Gerland, MS -03

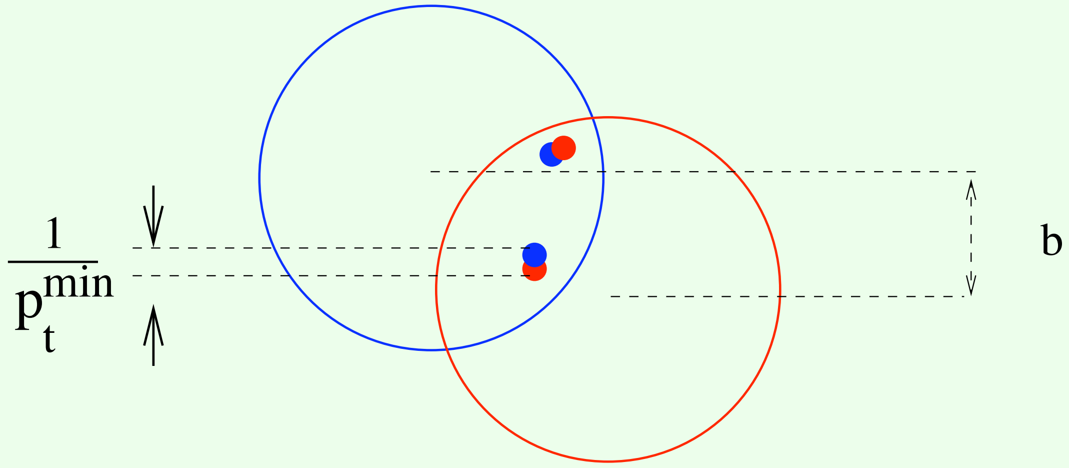


Longitudinal (integrated over p_t) and transverse distributions in CGC model for central pA collisions. (DGS -03).

Multi-jet production - study of parton correlations in nucleons

a) b)

Where is the infinite number of primordial 'sea' partons in the infinite momentum state of the proton: inside the constituent quarks (a) or outside (b) ?



A view of double scattering in the transverse plane.

At high energies, two (three ...) pairs of partons can collide to produce multijet events which have distinctive kinematics from the process two partons → four partons.

In pp scattering one measures a product of $f(x_1, x_2)$ - longitudinal light-cone double parton density and ``transverse correlation area" - $\sqcup_{eff}$ .CDF observed the effect in a restricted kinematics and found $\sqcup_{eff}$ ~ 14 mb rather small, indicating high degree of correlations in transverse plane.

Possible sources of small $\sqcup_{eff}$ include:

☺ Small transverse area of the gluon field --accounts for 50\% of the enhancement (FS & Weiss)

☺ Hot spots (QCD evolution) (A.Mueller)

☺ Constituent quarks - quark -gluon correlations

Need to check CDF results & measure $f(x_1, x_2)$ independent of σ_{eff}

Method: Study of the A-dependence (MS & Treleani 95 - 02)

$$\sigma = \sigma_1 \cdot A + \sigma_2$$

$$R \equiv \frac{\sigma_2}{\sigma_1 \cdot A} \approx \frac{(A-1)}{A^2 \cdot \sigma_{eff}} \int T^2(b)\, d^2b \approx 0.68 \cdot \left(\frac{A}{12}\right)^{0.39} \Big|_{A \geq 12, \sigma_{eff} \sim 14mb}$$

For σ_{eff} =14 mb and A~ 200 , R ~3 !!!

→ Can separate $\sigma_1 \& \sigma_2$ via A-dependence, study longitudinal correlations between the partons (spin effects?), and measure transverse separation between the partons.

Color fluctuations in the nucleon wave function & 3-dimensional mapping of the nucleon WF

Fluctuations of interaction strength are likely to be correlated with quark content of the hadron. Smallest configurations are most likely the minimal Fock state ones.

Important feature of QCD: QCD sum rules, form factors at large Q, chiral dynamics. Experimental evidence: Pion diffraction into two jets, inelastic coherent diffraction off nuclei.

Three methods of experimental study in pA scattering:

- Hard exclusive diffraction: $p + A \to 3\ jets + A$
- Soft coherent diffraction: $p + A \to X + A$
- Associated hadron production in hard pA processes involving a leading quark (gluon) in the proton:

$$p + A \to \mu^+\mu^- + hadrons\ (at\ y \sim 0, y \sim y_A)$$

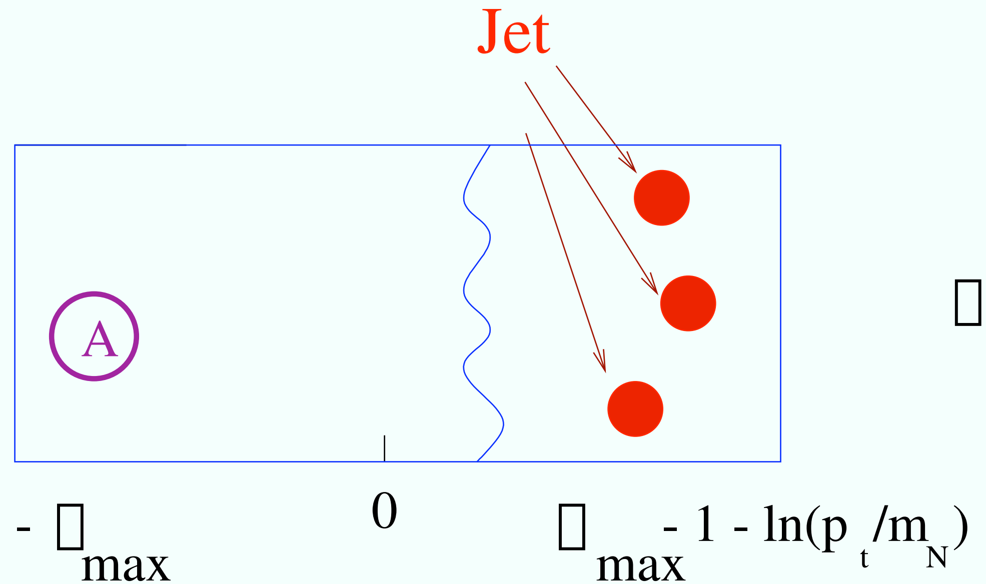
Very forward physics: $p + A \rightarrow 3\ jets + A$

- Measurement of the proton wave function in $|3q>$ configuration with small transverse distance separation.

- Color transparency & Color opacity

Extension of the study of $\Box + N(A) \rightarrow \text{“}2\ high\ p_t\ jets\text{''} + N(A)$

by FNAL 791 (2001), which confirmed Miller &F&S 93 prediction for the A-dependence, z-, p_t-dependence of the dijet coherent cross section.



Lego plot for coherent 3 jet production
in proton -nucleus scattering

$$\frac{d\sigma(pA \to (jet_1 + jet_2 + jet_3) + A)}{dt \prod_{i=1}^{3} dx_i d^2 p_{ti}} \quad \left[\alpha_s x_A G_A(x_A, p_t^2)\right]^2 \cdot$$

$$\cdot \frac{\psi_N^2(x_1, x_2, x_3)}{\prod_{i=1}^{3} p_i^4} \delta^2\left(\sum_{i=1}^{3} \vec{p}_{ti} - q_t\right) \delta\left(\sum_{i=1}^{3} x_i - 1\right) G_N^2(t) F_A^2(t),$$

$where\ t = -q_t^2, x_A = M_{3\,jet}^2/2s, \psi_N$ nucleon 3 q wave function.

Advantages of the collider kinematics: it is easy to select coherent processes using zero angle neutron calorimeter. Energy dependence is very strong if there is no taming of gluon densities since

$$xG_A(x, Q^2 \sim 40\ GeV^2) \quad \frac{1}{\sqrt{x}} \qquad \Longrightarrow \quad \square_{3\ jet} \quad s\ !!!$$

At RHIC one can hope to distinguish three jet configurations with

$p_t \geq 3\ GeV/c$ corresponding to $x = \frac{M^2_{3\ jet}}{s} = \frac{9p_t^2}{s} \sim 10^{-3}$

For such transverse momenta shadowing is rather weak function of A

$$xG_A \quad A^{-0.1} \qquad \Longrightarrow \square_{3\ jet}(A) \quad A^{1.1}\ as\ compared\ to\ \square_{soft\ diffr.} \quad A^{0.6}$$

The magnitude of the cross section is $10^{\square 5}$ mb per nucleon.

Comments:

- If diquark-quark correlations are present in nucleons, one can look for 2 jet fragmentation.
- Interesting to search for exclusive channels at smaller p_t like $p \to p\square^+\square^-, \square K^+$ to find an effective trigger for interaction in point like configuration. If this would work can use double diffraction in pp scattering as a trigger for the scattering of two small dipoles.

Conclusions: *Strong case for expanding the acceptance of the RHIC detectors (new detector?) in the very forward region. In pA mode this would allow to obtain unique information on*

◈ *Small x parton densities*

☛ Forward detector would allow to measure gluon and quark shadowing down to the region where taming effects as well as absolute magnitude of shadowing are large.

☛ x-range will nicely complement & overlap with Ultraperipheral Collision range at LHC as well with eRHIC range allowing tests of violation of pQCD factorization.

☛ Black body limit predicts drastic changes in the p_t broadening, dependence of the cross sections on virtualities, etc.

Mapping of the proton wave function

- Multiparton correlations in nucleons (3D-picture)
- Measurement of three quark component of the nucleon wave function.
- Color fluctuations in nucleons: global effects & x-dependent effects